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Extreme value analysis of streamflow time series in Poyang Lake Basin, China

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Abstract: Extreme meteorological and hydrological events may cause major disasters and heavy social and economic losses. Therefore, more and more studies have focused on extreme hydro-meteorological events in various climates and geographic regions. Based on nearly 50 years of observed records of the Poyang Lake Basin, the occurrence and changing trends of extreme streamflow indices, including the annual maximum flow, annual peak-over-threshold flows, and low flows, were analyzed for ten hydrological stations. The results indicate that most annual maximum flows occurred from April to July, highly attributed to the Southeast Asian summer monsoons, whereas the annual minimum flows were concentrated between January and February. As for the low flow indices (the annual minimum flow, annual minimum 7-d flow, and annual minimum 30-d flow), a significant increasing trend was detected in most parts of the Poyang Lake Basin. The trends illustrate the potential effects of climate change and human activities on the hydrological cycle over the Poyang Lake Basin.

Key words: *Poyang Lake Basin; extreme streamflow event; Mann-Kendall test; directional statistics*

1 Introduction

Extreme meteorological and hydrological events all over the world may lead to major disasters and result in heavy social and economic losses, and even severe health consequences. Concerns over these extreme events have been increasing in recent decades (Houghton et al. 2001). In previous studies, significant changes of extreme streamflow were reported in some regions through investigation of the observed data. In Europe, significant positive flood trends were detected in the northern part (Kundzewicz and Robson 2004; Lindström and Bergström 2004). Douglas et al. (2000) found increasing trends in low flow from the mid-west towards the northeast of the USA. In China, Zhang et al. (2005) evaluated the relations between

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temperature, precipitation, and streamflow of the Yangtze River Basin from 1951 to 2002, which suggests that the present global warming would intensify the flood hazards in the basin. Yang et al. (2010) investigated the low flow characteristics of the Yellow River, and found that the low flow regime of the middle and lower Yellow River was decreasing overwhelmingly. On the other hand, some research showed no significant change in extreme streamflow. For instance, there is no regional flood trends detected in the UK, as well as most of the USA (Kundzewicz and Robson 2004). According to these studies, the spatial patterns of changes in floods and low flows were complicated and various around the world (Zhai et al. 2010). The variation of extreme meteorological and hydrological events needs to be clarified.

The Poyang Lake Basin has been faced with serious water resources problems. Both droughts and floods have occurred frequently in the basin in recent decades. Moreover, floods have increased in their severity since 1990 (Guo and Jiang 2008). The most severe floods of the last five decades in Poyang Lake occurred in 1998, 1996, and 1995. The runoff coefficients of the Poyang Lake Basin increased significantly and changed abruptly in the late 1980s and the early 1990s (Guo et al. 2006). Zhao et al. (2010) found that the average annual streamflow of the Poyang Lake Basin increased significantly over the last five decades and streamflow is more sensitive to the changes in precipitation than evaporation. Although some efforts have been undertaken to detect the changes in extreme meteorological and hydrological events, the occurrence and changing trends of extreme streamflow in the Poyang Lake Basin have not been sufficiently and systematically addressed by using a suitable approach. In addition, the driving forces for the changes of the extreme hydrological events have not been clearly identified.

The objective of this study was to analyze the spatial and temporal variation of extreme streamflow in the Poyang Lake Basin in order to identify whether the extreme streamflow had significantly changed during the period from 1957 to 2003 under the impacts of climate change and human activities. In detail, we would like to quantify the occurrence and changing trends of extreme events by using the directional statistics and the Mann-Kendall test.

2 Study area and data

The Poyang Lake Basin, located in the middle reaches of the Yangtze River Basin (Fig. 1), China, covers an area of 162 200 km^2, which accounts for nearly 97% of the whole area of Jiangxi Province. Poyang Lake is a narrow outlet into the Yangtze River, which lies on the northern border of the province. As shown in Fig. 1, the five major rivers in Jiangxi Province flowing into Poyang Lake are the Ganjiang River, the Xiushui River, the Fuhe River, the Raohe River, and the Xinjiang River. The rivers downstream flow into the relatively broad alluvial valleys surrounding Poyang Lake. The Ganjiang River, extending 750 km, is the longest river in the region, which contributes more than 50% of the total discharge into Poyang Lake (Shankman et al. 2006). The whole basin is dominated by the Southeast Asian monsoon in summer, with the rainy season starting from April.

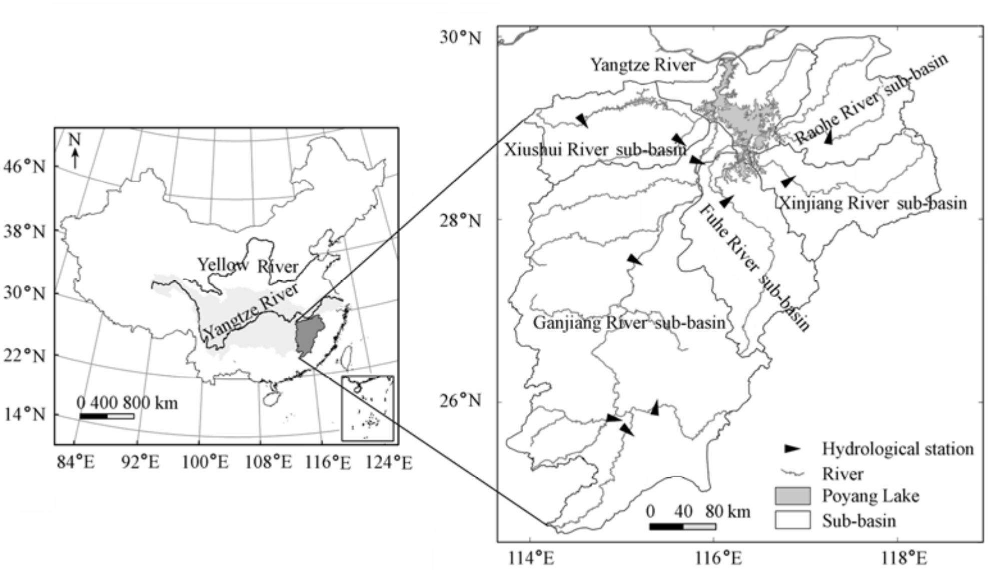


Fig. 1 Location of study area and hydrological stations in Poyang Lake Basin

In this study, the daily streamflow records from ten hydrological stations (shown in Fig. 1) in the five main tributaries of the Poyang Lake Basin were selected for investigation according to their lengths and continuities. The detailed information about the ten hydrological stations can be found in Table 1. The daily time series were validated by identifying and rectifying sequences of anomalous flows, and checking their completeness. Missing data were filled up by hydrological simulations. Of these stations, Hushan Station located in the Raohe River sub-basin has a two-year gap (1977-1978), which was filled up by a simple hydrological model implemented in PCRaster (Zhao et al. 2010).

Table 1 Detailed information of hydrological stations in Poyang Lake Basin

No.	Station	Drainage area (km^2)	Sub-basin
1	Bashang	7 657	Ganjiang River sub-basin
2	Julongtan	7 751	Ganjiang River sub-basin
3	Xiashan	15 975	Ganjiang River sub-basin
4	Xiajiang	62 724	Ganjiang River sub-basin
5	Waizhou	80 948	Ganjiang River sub-basin
6	Gaosha	5 303	Xiushui River sub-basin
7	Wanjiabu	3 548	Xiushui River sub-basin
8	Lijiadu	15 811	Fuhe River sub-basin
9	Hushan	6 374	Raohe River sub-basin
10	Meigang	15 535	Xinjiang River sub-basin

In this study, we selected six indices to describe the characteristics of the extreme streamflow including both low flow and high flow: the annual minimum flow ($Q_{\min}$ (m^3/s)), annual minimum 7-d flow ($Q_{7\text{-d}\min}$ (m^3/s)), annual minimum 30-d flow ($Q_{30\text{-d}\min}$ (m^3/s)), annual maximum flow ($Q_{\max}$ (m^3/s)), and annual peak-over-threshold flows (Q_{POT95} (m^3/s) and Q_{POT99} (m^3/s)).

$Q_{\max}$ represents the maximum value of the flood events in each year, and only one value is detected every year. It represents the largest streamflow value of several observed high discharge values in wet years, whereas a relatively low flow value that may not necessarily be characterized as a flood at all in dry years will be selected (Svensson et al. 2005). A more representative way to describe the frequency of high flows in a continuous record is using a peak-over-threshold (POT) series consisting of a series of independent daily mean flows that exceed a certain threshold (Svensson et al. 2005). The thresholds with 95 percent (Q_{POT95}) and 99 percent (Q_{POT99}) values of the daily discharge records at each station were selected to describe the magnitude and frequency of the extreme high flows.

$Q_{\min}$, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$ were selected for low flow analysis. $Q_{7\text{-d}\min}$, known as dry weather flow, is commonly used for low flow analysis (Yang et al. 2010). Comparably, the analysis of $Q_{7\text{-d}\min}$ and $Q_{30\text{-d}\min}$ based on a time series of long-duration low flows is less sensitive to measurement errors.

3 Methodologies

3.1 Directional statistics

Directional statistics is concerned mainly with observations that are unit vectors in the plane or in the three-dimensional space (Mardia 1999). The sample space is typically a circle or a sphere, so that the occurrence of $Q_{\max}$ and $Q_{\min}$ can be assumed to be an object in an annual circle, and thus be described by means of directional statistics. So far, directional statistics has been widely applied in the hydro-climatic field (Bayliss and Jones 1993; Cunderlik and Ouarda 2009). This approach transforms the original occurrence dates of individual extreme events into a directional variable. Taking $Q_{\max}$ as an example, θ_i is an angular value that denotes the Julian date (D_i) on which $Q_{\max}$ occurs in the ith year, and can be converted by

$$\theta_i = D_i \frac{2\pi}{d}, \ 0 \le \theta_i \le 2\pi \tag{1}$$

where d is the number of days in a year equal to 365, or 366 for a leap year.

To identify the characteristics of the occurrence and magnitude of $Q_{\max}$, the regularity of $Q_{\max}$ occurrence was introduced. The mean direction ($\bar{\theta}$) represents a directional location of a sample consisting of dates of flood occurrence. A convenient method for describing the variability of the individual dates of flood occurrence around the mean value can be defined as (Bayliss and Jones 1993)

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}, \ 0 \le \bar{r} \le 1 \tag{2}$$

where $\bar{r}$ is flow regularity, which is a dimensionless variable. A value of $\bar{r}$ close to 1 indicates high homogeneity of all events in the sample, while a value close to 0 indicates greater variability in the occurrence of flood events (Cunderlik and Ouarda 2009); $\bar{x}$ and $\bar{y}$ are the x- and y- coordinates of the mean date (m) of the occurrence of $Q_{\max}$ in a sample with N flood events at a station, and can be calculated as

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N}\cos\theta_i,\ \ \bar{y} = \frac{1}{N}\sum_{i=1}^{N}\sin\theta_i \tag{3}$$

where N is the number of flood events.

m represents a directional location measuring a series of dates for flood occurrence, and can be defined as

$$m = \bar{\theta}\frac{d}{2\pi N},\ \ \bar{\theta} = \tan\left(\frac{\bar{y}}{\bar{x}}\right) \tag{4}$$

3.2 Trend detection

A large number of parametric and non-parametric methods have been successfully applied in hydro-climatic series analysis (Li et al. 2009; Zhao et al. 2009). In this study, we analyzed the temporal trends of extreme streamflow indices by using both the least square test and the non-parametric Mann-Kendall (MK) test (Mann 1945; Kendall 1975). The MK test has been widely applied to detecting a trend in hydro-climatic time series (Yue and Wang 2002; Novotny and Stefan 2007; Li et al. 2009). The details of the method have been described in previous literature (Novotny and Stefan 2007; Zhao et al. 2009).

The MK test requires the time series data to be serially independent (Yue and Wang 2002). The present study undertook the serial correlation detection by examining the autocorrelation coefficients of the time series. As shown in Fig. 2, almost all of the coefficients are lower than the 95% confidence level, which means that the streamflow series ($Q_{\max}$, $Q_{\min}$, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$) are time independent.

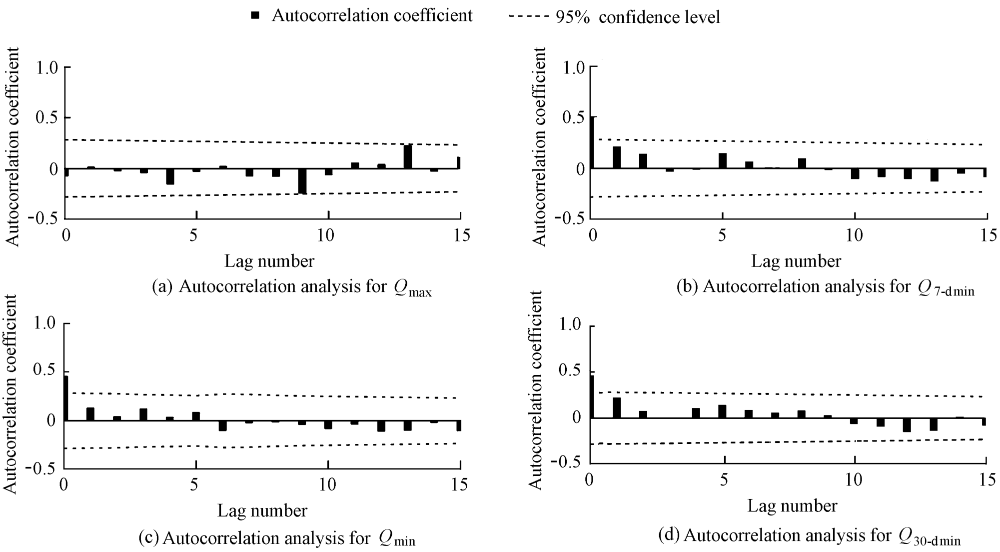


Fig. 2 Autocorrelation analysis of streamflow time series at Xiashan Station during period from 1957 to 2003

4 Results and discussion

The occurrence and magnitude of Q_{max} and Q_{min} events were extracted from the continuous daily streamflow records at ten hydrological stations in the Poyang Lake Basin. The occurrence of the extreme events was detected by directional statistics. Both the simple linear test and the MK test were used for assessment of the variability of trends in extreme flow indices.

4.1 Extreme event occurrence

Fig. 3 shows the distribution of dates for Q_{max} and Q_{min} events at Waizhou Station during the period from 1957 to 2003 (as points plotted on a unit circle, respectively). From Fig. 3(a), it can be seen that Q_{max} mostly occurred from April to July. The Poyang Lake Basin lies in a wet climate zone, which is dominated by the Southeast Asian monsoon in summer. The summer monsoon brings atmospheric moisture into the basin, leading to large amounts of rainfall during the wet season. According to the monthly precipitation distribution, rainfall was mainly concentrated between March and June, which caused Q_{max} to occur in the wet season (Zhao et al. 2010). Fig. 3(b) indicates that Q_{min} occurred from October to March in the following year.

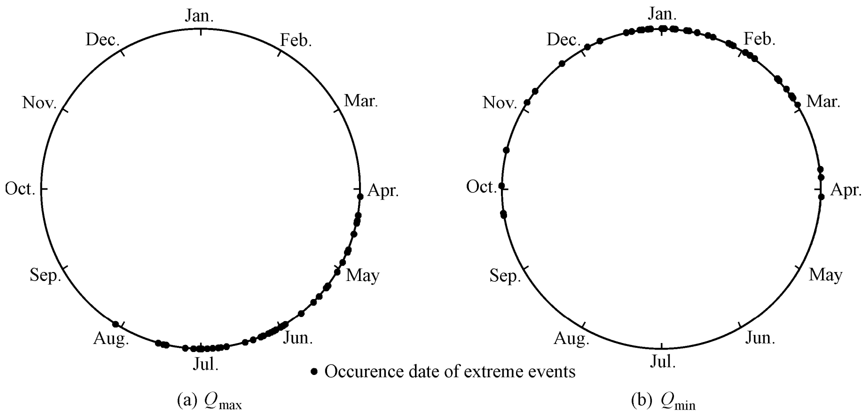


Fig. 3 Occurrence of Q_{max} and Q_{min} at Waizhou Station in Poyang Lake Basin

Generally speaking, the extreme events obviously illustrated the seasonality of precipitation. Q_{max} occurred in the wet season in a year from April to August, whereas Q_{min} occurred in the dry season from October to March in the following year. On the other hand, the occurrence dates of Q_{max} were concentrated in a shorter period (three to four months) than those of Q_{min} (about six months). This may be associated with the regional climate patterns and monsoon activities.

Fig. 4 shows the seasonality and flow regularity of Q_{max} and Q_{min}. It reveals a high degree of seasonality of floods and droughts, since there is a comparatively small range of the values for the mean dates of the occurrence of Q_{max} and Q_{min}. All the mean dates of the occurrence fall within May 20 to June 20 for Q_{max}, and December 25 to February 2 for Q_{min}.

Previous studies have also found the highest flood frequency in June in the Poyang Lake Basin (Guo et al. 2006). Also, the occurrence of Q_{max} and Q_{min} is fairly regular in the Poyang Lake Basin, implying a low variability in the occurrence dates of Q_{max} and Q_{min}, with values of $\overline{r}$ ranging from 0.635 to 0.855, and 0.405 to 0.785, respectively. Through comparison, the broader range of low flow regularity indicates a higher variability of extreme drought events.

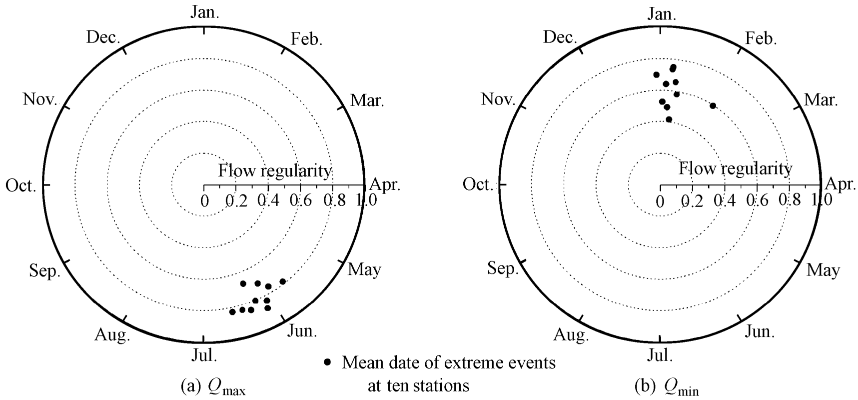


Fig. 4 Seasonality of Q_{max} and Q_{min}, and flow regularities at ten stations

4.2 Trend analysis

Both the MK test and the least square test were applied to examining the temporal variation of extreme streamflow series (Q_{max}, Q_{min}, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$) at ten hydrological stations in the Poyang Lake Basin. Considering the homogeneity of some stations in the same sub-catchment, we chose six stations (Xiashan, Waizhou, Hushan, Meigang, Wanjiabu, and Lijiadu) in five sub-catchments for the trend analysis.

The annual variations of $Q_{7\text{-d}\min}$ trends estimated by the simple linear method in the Poyang Lake Basin are shown in Fig. 5. Notable upward trends were detected in the time series of $Q_{7\text{-d}\min}$ among most of the stations, except Lijiadu Station. $Q_{7\text{-d}\min}$ at Waizhou Station downstream of the Ganjiang River shows an evident upward trend with a mean annual increase of 3.70 m^3/s. In contrast, $Q_{7\text{-d}\min}$ at Lijiadu Station shows a downward trend with a mean annual decrease of 0.27 m^3/s (as shown in Table 2). This finding is consistent with the average annual streamflow trends in the Poyang Lake Basin (Zhao et al. 2010). The main reason for the abnormal trends of extreme flow events at Lijiadu Station may result from the non-significant changes of precipitation in this catchment.

Table 2 displays the linear trends of Q_{max}, Q_{min}, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$. The positive values indicate that the series have increasing trends, and vice versa. In general, Q_{max} did not show evident trends at most stations for the study period, and the changing trends ranged from –11.79 to 29.15 m^3/s. As for low flows, notable results can be found at most stations except for Lijiadu, illustrating upward trends for Q_{min}, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$. As shown in Table 2, the trends at Waizhou and Xiajiang stations in the Ganjiang River sub-basin are more significant with upward trends from 2.51 to 5.15 m^3/s, which is attributed to large daily average discharges at these two stations (Fig. 5). Similarly, Guo et al. (2006) found significant increasing trends for $Q_{7\text{-d}\min}$ at most stations across the whole basin. According to our analysis, the increasing trends for the extreme low flows were due to both the increasing annual precipitation and anthropologic activities. There is no evident trend for $Q_{\max}$, although most studies indicated significant increasing trends in both annual precipitation and summer rainfall (Guo and Jiang 2008; Zhao et al. 2010). Many studies have investigated whether extreme high or low flows are associated with climate change or land-use/land-cover change and concluded that both climate change and human activities (like reservoir operation) should be considered in assessing the impacts of environmental changes on streamflow processes (Wang et al. 2008).

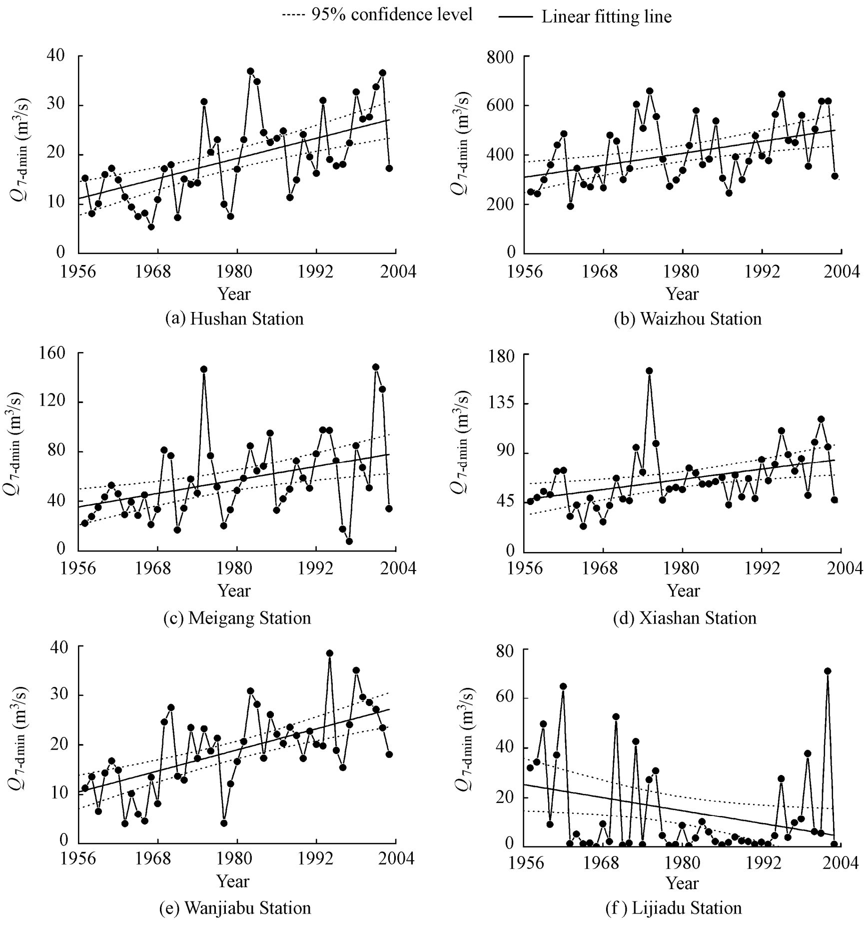


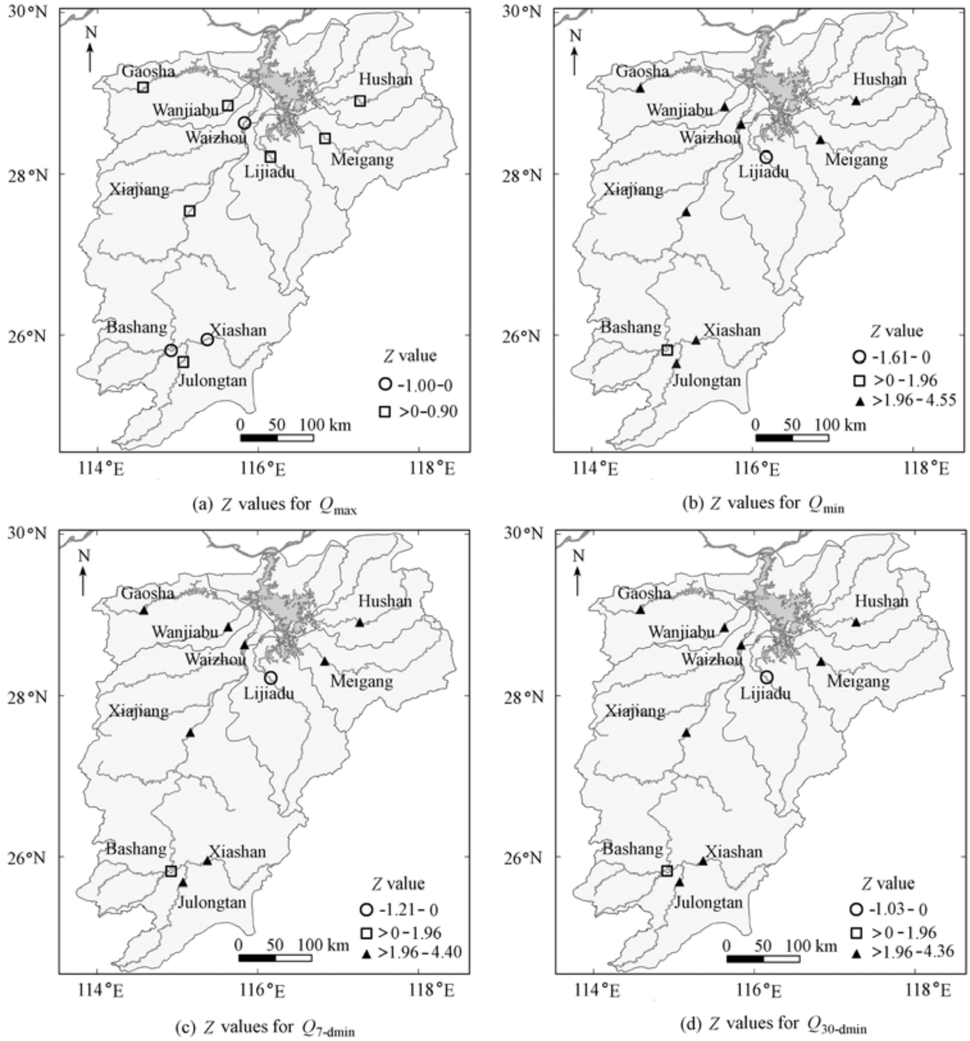
Fig. 5 Variation of $Q_{7\text{-d}\min}$ for six hydrological stations of Poyang Lake Basin

The trends of the extreme streamflow series ($Q_{\max}$, $Q_{\min}$, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$) for each hydrological station in the Poyang Lake Basin were analyzed with the MK test method at a significance level of 0.05. The statistic Z reflecting the time series changing trends was calculated (Fig. 6). The Z value is equal to ±1.96 at the significance level of 0.05.

Table 2 Mean annual increment of extreme streamflow series in Poyang Lake Basin (m^3/s)

Station	Mean annual increment			
	Q_{max}	Q_{min}	$Q_{7\text{-d min}}$	$Q_{30\text{-d min}}$
Bashang	3.35	−0.08	0.19	0.31**
Julongtan	−4.53	0.38**	0.41**	0.46**
Xiashan	−3.47	0.73**	0.75**	0.77**
Waizhou	−11.79	3.45**	3.70**	5.15**
Gaosha	3.14	0.22**	0.31**	0.44**
Wanjiabu	6.77	0.36**	0.36**	0.38**
Lijiadu	11.68	−0.25*	−0.27	−0.13
Hushan	8.34	0.34**	0.37**	0.39**
Meigang	29.15	0.85**	0.93	1.52**
Xiajiang	0.77	2.51**	3.30**	4.85**

Note: ** denotes trend at 0.001 significance level, and * denotes trend at 0.01 significance level.



(a) Z values for Q_{max} (b) Z values for Q_{min}

(c) Z values for $Q_{7\text{-dmin}}$ (d) Z values for $Q_{30\text{-dmin}}$

Fig. 6 Extreme flow trends detected by MK method in Poyang Lake Basin

As shown in Fig. 6, Z values for $Q_{\max}$ range from –1.00 to 0.90, which illustrate that there are no significant trends for $Q_{\max}$ at all stations. Generally, the MK test results are consistent with linear trends as displayed in Table 2, and only three stations (Bashang, Waizhou, Xiashan) in the Ganjiang River sub-basin show downward trends, but not significantly. Comparably, the results of trend analysis for low flows are most insightful, indicating similar trends obtained by examining $Q_{\min}$, $Q_{7\text{-d}\min}$, and $Q_{30\text{-d}\min}$ (Fig. 6). Among the ten hydrological stations, only two stations (Lijiadu and Bashang) did not show significant increasing trend at the 95% confidence level. The increasing precipitation, to some degree, is associated with the increasing trends of the extreme low flows. According to previous studies, Zhao et al. (2010) found that the streamflow increased significantly at a 95% confidence level except for Lijiadu Station in the dry season, which might be due to the non-significant changes of the precipitation at this station.

Similar linear trends were found in Q_{POT95} and Q_{POT99} in the Poyang Lake Basin. Here we only present the variation of Q_{POT95} and the annual number of days above Q_{POT95} (Fig. 7). The results indicate that there are no significant trends for all the stations, which is similar to $Q_{\max}$, as described above. As shown in the figure, a relatively wet period is detectable according to both the mean discharge values and the annual number of days above the Q_{POT95} since the beginning of the 1990s. This is also consistent with the investigation result in Guo and Jiang (2008) in the Poyang Lake Basin: they found that the frequency of extreme precipitation had become increasingly significant since 1990 and extreme events were becoming more concentrated in shorter periods. This might be attributed to the weakened thermal contrast between the tropical ocean and the Asian inland region, which causes a weaker summer monsoon that stays longer in the Yangtze River Basin and results in quasi-stationary fronts with heavy rainfall systems from late spring to midsummer (Wang and Zhou 2005).

5 Conclusions

In this study, we selected six extreme streamflow indices, $Q_{\max}$, $Q_{\min}$, $Q_{7\text{-d}\min}$, $Q_{30\text{-d}\min}$, Q_{POT95}, and Q_{POT99}, to examine their occurrence and spatio-temporal trends in the Poyang Lake Basin. The main conclusions are as follows:

(1) A good seasonality of floods and droughts can be clearly found in the Poyang Lake Basin. The occurrence dates of $Q_{\max}$ and $Q_{\min}$ are concentrated in the period from May to June, and from December to February in the following year, respectively. The occurrence of $Q_{\max}$ and $Q_{\min}$ is fairly regular in the Poyang Lake Basin, implying low variability in the dates of $Q_{\max}$ and $Q_{\min}$, with extreme flow regularity ranging from 0.635 to 0.855 and from 0.405 to 0.785, respectively.

(2) There is generally a good agreement between the results of the trend analysis using the linear regression method and the MK method. The major hydrological characteristics of $Q_{\max}$, Q_{POT95}, and Q_{POT99} are shown to have no statistically significant trends at most stations

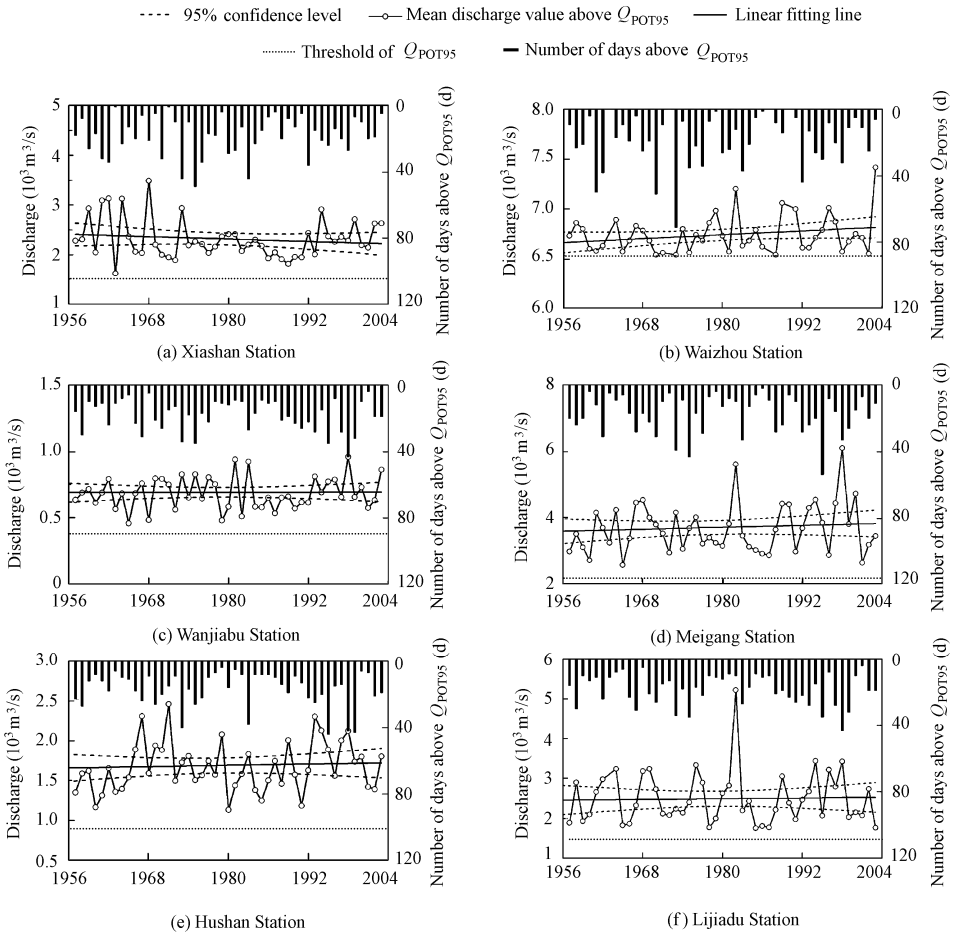


Fig. 7 Mean discharge above Q_{POT95} and number of days above Q_{POT95} at six hydrological stations in Poyang Lake Basin

in the whole basin. The extreme low flows have significant increasing trends, particularly at Waizhou and Xiashan stations. The MK test shows that Q_{min}, $Q_{7\text{-}d\,min}$, and $Q_{30\text{-}d\,min}$ in most parts of the Poyang Lake Basin displayed significant increasing trends.

(3) The main factors leading to complicated trends of extreme streamflow may result from spatial and temporal differences of precipitation, together with the impacts of intensive human activities on hydrological processes. Further investigation should be undertaken to thoroughly explain how these factors influence the extreme streamflow in the Poyang Lake Basin.

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